

Detection of geodynamic activity areas based on the Earth's electromagnetic noise parameters

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Abstract. In this paper, a method of using the Earth's natural pulsed electromagnetic noise for mapping of anomalies of intensely strained state of the Earth's crust is substantiated. Examples of using the method for mapping of geodynamically dangerous sites and monitoring of processes that pose threats to the operation of industrial facilities are presented.

1. Separating space and time variations in a flow of EM signals

Natural pulsed electromagnetic fields are mostly produced by shallow crustal discontinuities, cracks and microcracks. Electromagnetic noise patterns have been employed for mapping faults, monitoring stress and strain in the ground, and for predicting geodynamic movements since the beginning of PEMF studies [1, 2], though they remain of almost no use in geophysical prospecting applications. The lithospheric component of pulsed EM responses becomes prominent only if the instruments are sensitive enough [3, 4] but records of very sensitive acquisition systems are very noisy and abound in atmospheric signals. On the other hand, low sensitive systems record only the heaviest thunderstorms and miss lithospheric responses. Thus, the data acquisition units have to be adjusted to a certain optimum sensitivity range depending on local ground properties. It is convenient to tune instruments against empirical calibration relationships, based on years-long measurements of the Earth's natural pulsed electromagnetic field in different parts of Eurasia. In this it is important that the behavior of the recorded time series were proximal to diurnal ENPEMF rhythms typical of a given season [4, 6]. The precision of ENPEMF measurements is about 10 nT. One has to take into account that about 90 % of responses come from sources outside the target objects and cannot represent their geology. The way of picking spatial ENPEMF anomalies from the flow of recorded signals has been patented (RF Patent No. 2414726) [5].

In the suggested approach, atmospherics and remote responses from objects outside the area of interest are removed from the flow of recorded signals. Filtering from irrelevant components is provided at the stage of data acquisition and processing by:

- using a network of synchronously operated largely spaced fixed and mobile EM stations;
- tuning the stations to the optimum sensitivity and checking their consistency in terms of sensitivity and precision;
- discriminating between remote and local responses.



PEMF signals vary both in space and time. The fixed stations in ENPEMF systems record only variations in time and serve for reference, while the others are mobile and sample both temporal and spatial field patterns along profiles that cross the target areas. The systems include at least two receivers, the greater their number the better the resolution.

Local and remote responses can be discriminated according to their amplitude and time of arrival at distantly spaced stations. Remote responses (e.g., atmospherics) propagate along the Earth-ionosphere waveguide to arrive at proximal stations almost simultaneously, and have the same amplitudes. Responses of large lithospheric objects reach the surface and travel further as ground rays at about the light speed and decay very slowly, which provides their synchronous recording at all stations with similar amplitudes.

Unlike the remote signals, local responses travel mostly through rocks in the vicinity of stations. Signals immediately over the source and those from more distant points have markedly different amplitudes because of rapid decay. In threshold acquisition systems that cut off low signals, more distant receivers can record fewer responses than those located near the anomaly. However, prominent local responses recorded by all distantly spaced stations have different amplitudes depending on the source-receiver distance, which is employed in the instruments and techniques we suggest.

2. Mapping stress and strain of rocks and faulting patterns

As it was mentioned above [6], natural Earth's EM noise results from crustal discontinuities, domains of high stress and strain, cracks and microcracks. Mechanic-to-electric energy conversion under the effect of strain waves from the mantle, tides, microseisms, winds, and technological loads produces pulsed EM fields which make up the natural lithospheric EM background. According to long-term measurements in different areas, lithospheric ENPEMF responses have well-defined diurnal and seasonal rhythms because crustal strain waves are associated with Earth's rotation about its axis and about the Sun. The diurnal cycles depend on the calendar dates, geographic coordinates, and geophysical properties. Typical diurnal variations respond to changes in crustal rhythms, for instance, when a consolidated domain of several interlocked fault blocks forms during earthquake nucleation or when stress and strain change rapidly. Thus, ENPEMF measurements can provide a universal tool for geophysical surveys and geodynamic monitoring or for any other application in geosciences.

We applied ENPEMF surveys to assess slope stability in the Kama River right bank in central Russia where the Urengoi – Pomary – Uzhgorod gas pipeline crosses the river. There is a cascade of landslides in the slope, which pose serious hazard to the line. During 1D profile surveys, one reference station was fixed and sampled ENPEMF temporal variations. It was placed ~150 m away from the slope, on a flat surface outside the landslide zone, and the slope stability and stress-strain patterns in the landslide were estimated against its data. Before the acquisition, the stations were synchronized with clocks built into MGR recorders, to fractions of a second. This allowed removing the responses that arrive simultaneously at all stations and thus come from outside the landslide. Information was inferred from the profile-to-reference station ratios of the measured parameters. Sampling at all stations was every 1 s (i.e., at least 300 counts at each point). Statistical processing included filtering the data from diurnal cycles and remote responses. Measurements were run along eleven profiles, both along and across the slope. In addition to measuring stress and strain in the southern part of the landslide, surveys along profile 1, upslope from the river, between pipelines one and two, aimed at estimating whether the detected anomalies remained stable with time. Each point was sampled twice by two different stations, 20 minutes one after another, which allowed testing the measurement quality and checking the anomalies in a while after the first sampling.

Repeated measurements at station 2 were taken 20 min after sampling at station 4; the EM noise patterns used to infer stress and strain in the southern part of the pipeline are shown in Figure 1.

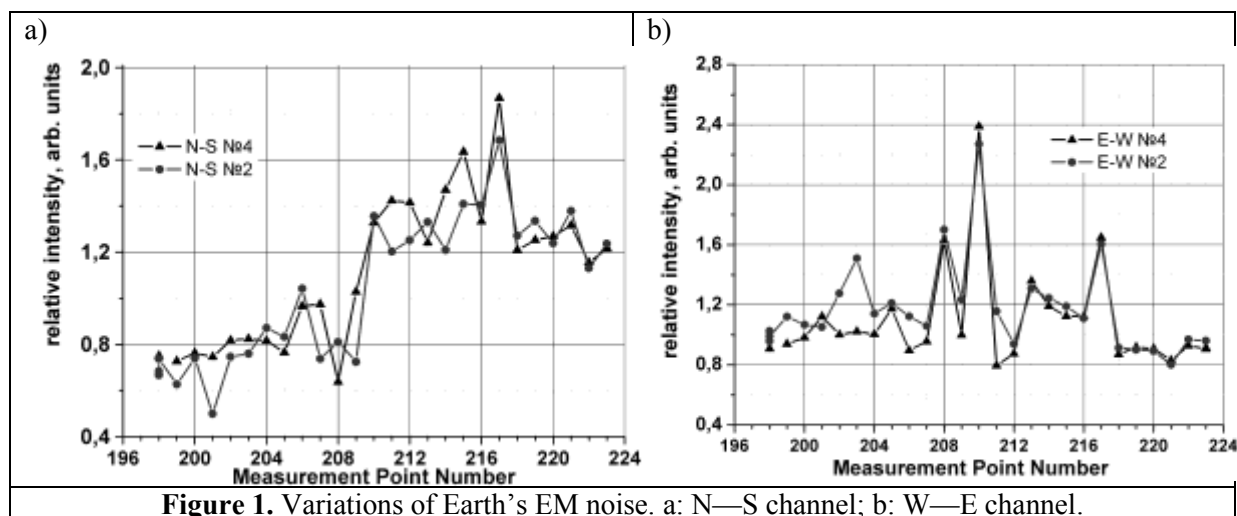


Figure 1. Variations of Earth's EM noise. a: N—S channel; b: W—E channel.

The results from different stations obviously remain consistent after filtering out the time component of ENPEMF. The highest landslide activity is recorded in the steepest part of the slope. Spatial variations are quite stable and hold with time. The spatial ENPEMF pattern remains almost invariable at least for 20 min and persists within some region of scatter. However, this stability may be upset either by interior processes inside the landslide or by exterior triggers, such as seasonal changes in ground moisture, snow melting, long rainfalls, technological loads, etc.

Images in Figure 2 are processed 2D data. Alternating zones of extension and compression are restricted mainly to the northern and central parts of the landslide slope. They appear as peaks and troughs in the 3D model above, with their heights and depths proportional to the stress magnitude, and as red or blue zones, respectively, in the map below.

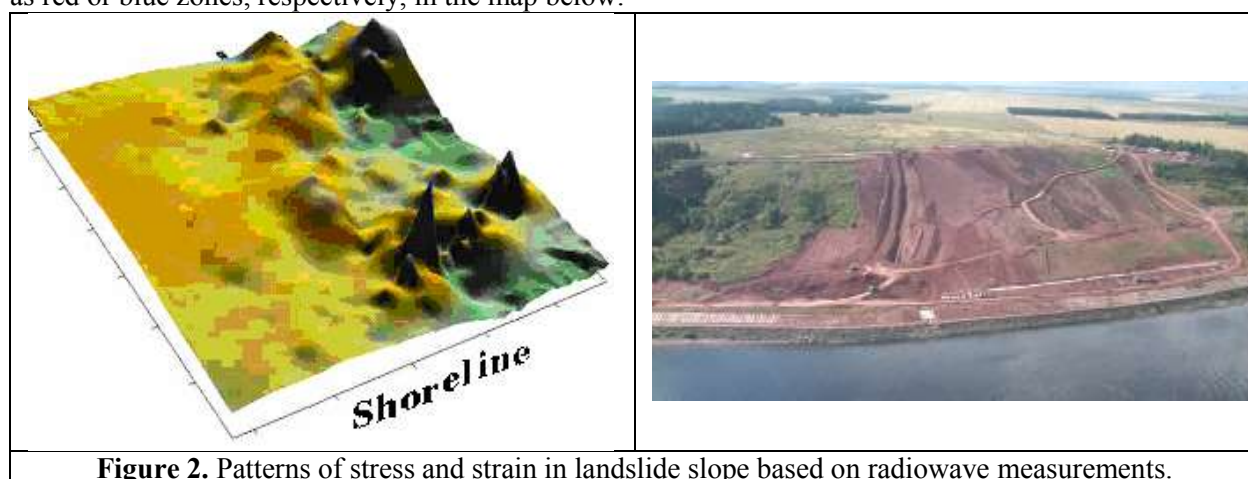


Figure 2. Patterns of stress and strain in landslide slope based on radiowave measurements.

Zones of extension, as well as their sharp borders with compression zones, are especially hazardous for pipelines. The most active landslide zones are located on the right, both in the 3D model and in the map (Figure 2), where exactly the compression and extension stresses are the highest and where most of pipeline accidents occurred for the past years. Thus, the ENPEMF method, being cheap and straightforward, turns out to be no less informative than geomorphological analysis, seismic survey, or drilling.

The data from the landslide slope of the Kama right bank demonstrate the applicability of PEMF surveys to estimating stress and strain of rocks. According to evidence of multiple tests, with repeated surveys, synchronous sampling at several stations, and checks against the classical methods, the

appropriate use of the ENPEMF techniques ensures precise, well reproducible, and reliable records of slope activity.

Thus records of the Earth's natural pulsed EM field can highlight zones of high and low sliding activity in unstable slopes, as well as zones of extension and relative compression and stress directions.

3. Monitoring of sliding activity in unstable slopes, assessment of the degree of their danger

In the end of 2007 an automatic system for slope stability monitoring was launched within the Urengoi – Pomary - Uzhgorod pipeline in the area where it crosses the Kama. The system currently comprises twelve multichannel stations MGR-01 deployed at sites of prominent stress-strain anomalies chosen proceeding from geophysical data. The stations consist of a recorder, a receiving antenna, and a battery, all placed in a tight container transparent for radiowaves. The containers are buried under the ground to avoid damage from vandalism while the transmitter GPS antennas emerge on the ground surface and are naturally camouflaged. The reference station (T4rep) is set up on the flat surface about 80 m away from the slope. Data from the other stations are processed with regard to temporal variations of ENPEMF parameters from the reference station. Furthermore, special smart devices (UB) pick up strain of metal in all nine pipes of the line on the slope top and at its base.

The EM noise data are saved in the recorder's memory and are available for reading on a PC or for sharing via a password-protected FTP web server. The recorded field parameters are collected, processed, and visualized at a specially designed web portal [7] equipped with all necessary tools. In the database created at the portal, the processed data are available in a graphic form or in a mode of hazard monitoring, which allows automatic assessment of slope stability at certain sites according to analysis of data in a data page.

Figure 3 shows a window a portal user sees. The ENPEMF data are visualized as curves in

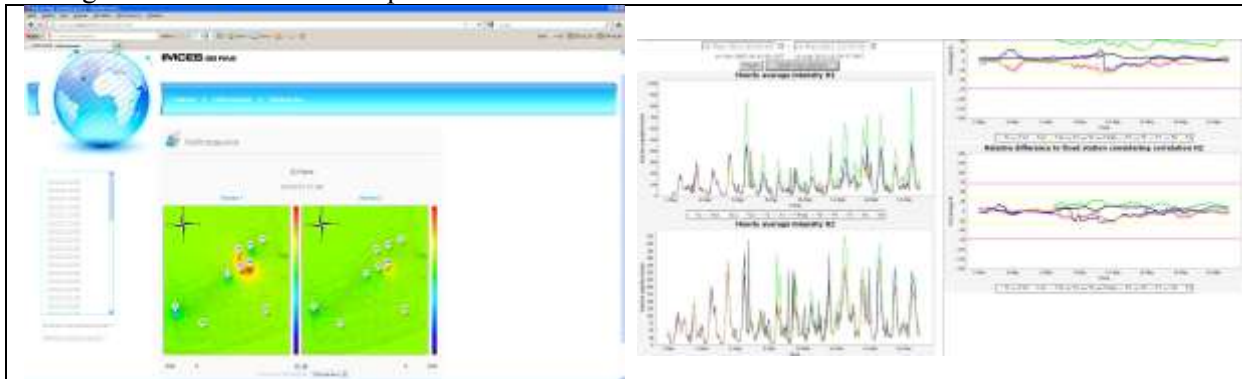


Figure 3. The view of a window at the web portal.

two radiowave channels (N—S channel H1 and W—E channel H2). Stress and strain data at the monitored landslide sites are available as color-coded curves and provide information on sliding hazard. The greater the curve departure from zero (green line) the more rapidly stress and strain change at the respective PEMF measurement point.

The algorithm of slope stability monitoring from PEMF parameters employs two criteria: one shows the field recorded on the slope relative to that at the reference station and the other estimates the similarity of data from different stations. The excess flow of ENPEMF signals at each station (T1, T2, T3, T5, T6, T7, T8, T9, T10, T11, T12) relative to the reference field at T4rep is found as

$$K_{(C-I0)} = \frac{(N1_{T(i)} - N1_{T(r)})}{N1_{T(r)}},$$

$$K_{(3-B)} = \frac{(N2_{T(i)} - N2_{T(r)})}{N2_{T(r)}}$$

- where $N1_{T(i)}$ is the flow of ENPEMF signals in the N—S direction at the i -th station; $N2_{T(i)}$ is the flow of ENPEMF signals in the W—E direction at the i -th station;;
- $N1_{T(r)}$, $N2_{T(r)}$ are the flows of ENPEMF signals in the N—S and W—E directions at the reference station.

The coefficients $K < 0$ correspond to compression in the respective direction (N—S or W—E) and $K > 0$ correspond to extension, the higher the K value the greater the stress. This parameter is a main diagnostic criterion of the geodynamic state of ground.

The second parameter accounts for correlation between ENPEMF diurnal variations at the reference and i -th stations, with Spearman's rank correlation coefficient between the two statistical samples found as

$$r = 1 - \frac{6}{n^3 - n} \sum_{i=1}^n (x_i - y_i)^2, \text{ where}$$

n is the size of the sample (number of measurements used in the calculation);

x_i is the rank of the i -th element of the first sample in the sample itself (e.g., for the sample $\{5, 8, 4, 6\}$

$x_1 = 2, x_2 = 4, x_3 = 1, x_4 = 3$);

y_i is the rank of the i -th element of the second sample in the sample.

Then the integral slope stability coefficient is found as

$$R_{o\delta} = \frac{K + (1 - r)}{2}, \text{ where}$$

$R_{o\delta}$ is the integrate parameter of empirically estimated residual stability.

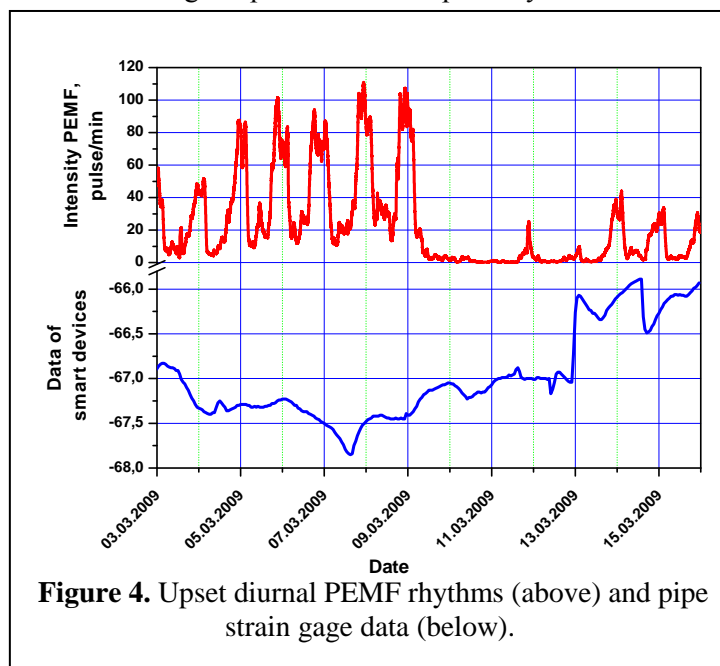


Figure 4. Upset diurnal PEMF rhythms (above) and pipe strain gage data (below).

appeared as upset diurnal rhythms persisting for several days. On these days, data from different slope stations differed markedly.

Once such field peaks appeared, gas transport from the hazardous line was moved to a standby line. Most often the Earth's EM noise records alerted before other monitoring devices became triggered.

An excess stability coefficient holding above 150% for three days or more indicates sliding hazard dangerous for the pipeline operation.

The suggested approach to ENPEMF data acquisition and processing provides precise and reliable assessment of slope stability (sliding activity, extension and compression, and stress directions) in real time.

Monitoring with our ENPEMF system in the course of several years has shown that different parts of the river side are dynamically developing structures and the slope stability within the landslide area can change locally even over 24 hours. ENPEMF anomalies were recorded more than ten times over the period of operation at different sites of the landslide and

The ENPEMF curve in Figure 4 is recorded near the gas line with pipe strain pickup (by a smart device). The common diurnal rhythm of EM pulses became upset on March 9, before ground motion showed up as a strain peak on March 13; the ENPEMF diurnal rhythm recovered in the end of the record.

The monitored pipeline segment ran smoothly, without any accident, for over 8 years of the ENPEMF system operation. Of course, it was largely due to preventive engineering measures undertaken in cases of alert. Currently, monitoring systems of this kind are being deployed elsewhere at sites of *Gazprom* pipelines.

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